ON THE MAINTENANCE OF THE MEAN ZONAL MOTION IN THE INDIAN SUMMER MONSOON

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ABSTRACT

The maintenance of the westerlies in the lower troposphere and the easterlies in the upper troposphere in the Indian southwest monsoon is studied by considering the angular momentum balance in the region. The main source term for the zonal angular momentum is the Coriolis or the Ω-transport term. This term contributes enough to maintain the lower tropospheric westerlies against friction. The zonal pressure gradient term and the mountain torque are of a smaller magnitude. The flux divergence at the boundaries is small in the lower troposphere; it is large in the upper troposphere and serves to export the easterly momentum produced in the region.

Thus, it is concluded that the mean meridional circulation (which is direct) mainly contributes to the maintenance of the mean zonal motion. Actually there is divergence of eddy flux of momentum from the region of maximum zonal winds. The mean meridional circulation releases kinetic energy of the same order of magnitude as the release by the mean winter meridional cell over an equal area.

1. INTRODUCTION

It is known that in the extratropics the meridional eddy transport of momentum contributes mainly [6, 24] or at least significantly [14, 22] to the maintenance of the mean zonal motion. In the Tropics, on the other hand, where the effect of the earth's rotation is less, the role of the mean meridional circulation has been stressed [11, 12, 13, 25]. Palmén [11] emphasizes the importance of the mean meridional circulation in the Tropics, in the budget of angular momentum, kinetic energy, and total energy. He adduces evidence from Fultz's laboratory experiments also and points out that the "Hadley regime" in the Tropics yields place to the "Rossby Regime" in the extratropics. Riehl [21] from energy budget considerations, concludes that the stationary part of the trade and monsoon regimes can provide for balance of heat, moisture, and kinetic energy and that unsteady flow features need not be involked for the maintenance of the tropical summer systems. In a coordinate system following the subtropical jet stream axis Krishnamurthi [8] found that to the south of the axis, the ageostrophic mass circulation transports much more angular momentum and total energy than the eddies. Rao [19] found that in the Indian region the meridional eddy transport of momentum is generally small except at the level of the easterly jet and that the advective transport is larger than the eddy transport at many stations. Sankar Rao and Ramanadham [23] found that the transient local eddy flux plays a relatively minor role in transporting heat or momentum poleward in the Indian region. Ananthakrishnan et al. [1] found that the Ω-transport term is one or two orders larger than the other meridional transport terms for Indian stations. Koteswaram [7] explained the zonal easterlies and westerlies in the Indian monsoon as resulting from the meridional circulation induced by the heat source over Tibet. Pisharoty [13] found that the kinetic energy produced by the meridional cell (Hadley) is about four times the production by eddies in the Tropics. Berson and Troup [3] in their study of angular momentum balance over the Australian region found that the Ω-transport term is large. In the numerical model experiment of the Indian monsoon by Murakami et al. [9] [1], the diabatic heating induces a meridional circulation, which by Coriolis turning results in the lower tropospheric westerlies and the upper tropospheric easterlies. Starting from radiation and other diabatic heat sources, they are able to arrive at the mean zonal motion in the monsoon.

Figures 1 and 2 show the mean wind charts for July for 700 mb. and 200 mb. taken from the mean charts of Raman [16] [2]. It is seen that they contain some aircraft mean winds over the oceanic region. The monsoon trough is seen over the northern parts of India. This extends from surface to 500 mb. with a southward slope. The monsoon westerlies to the south of the trough extend up to 500 mb. and give place to easterlies in the upper troposphere. Figure 3 shows the mean zonal winds for July averaged between 50°E. and 100°E. (taken from the above charts

[1] Also, talk by Murakami at the Institute of Tropical Meteorology, Poona, and personal discussions.

[2] The isotach analyses were also made for an earlier paper [17].

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of Raman). The square bracket indicates averaging between 50°E. and 100°E. The lower tropospheric westerly maximum and the upper tropospheric easterly maximum are seen. (The monsoon trough is blurred by the averaging.) Figure 4 shows the vertical profile of the mean zonal wind at Trivandrum (8.5°N., 76.9°E.) that records about the maximum in the westerlies and easterlies. The present study attempts to examine the maintenance of this mean zonal motion by considering the balance of angular momentum in the region, Equator to 20°N. and 50°E. to 100°E. (fig. 1).

2. EQUATION FOR THE BALANCE OF ANGULAR MOMENTUM IN A REGION

The equation for angular momentum balance in a region bounded by longitudes λ_1 and λ_2, latitudes ϕ_1 and ϕ_2, and pressure levels p_1 and p_2 is:

$$\begin{aligned}
\frac{a^3}{g}\frac{\partial}{\partial t}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2}\bar{u}\cos^2\varphi\, d\lambda\, d\varphi\, dp
&= -\frac{a^2}{g}\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2}\underset{\text{A}}{(\bar{u}^2+\overline{u'^2})\cos\varphi\, d\varphi\, dp\,\Big|_{\lambda_1}^{\lambda_2}}\\
&-\frac{a^2\cos^2\varphi}{g}\int_{\lambda_1}^{\lambda_2}\int_{p_1}^{p_2}\underset{\text{B}}{(\bar{u}\bar{v}+\overline{u'v'})d\lambda\, dp\,\Big|_{\varphi_1}^{\varphi_2}}\\
&+\frac{2\Omega a^3}{g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2}\underset{\text{C}}{\bar{v}\cos^2\varphi\sin\varphi\, d\lambda\, d\varphi\, dp}\\
&-a^2\int_{\varphi_1}^{\varphi_2}\int_{z_1}^{z_2}\underset{\text{D}}{p\cos\varphi\, d\varphi\, dz\,\Big|_{\lambda_1}^{\lambda_2}}-a^2\int_{\varphi_1}^{\varphi_2}\int_{z_1}^{z_2}\underset{\text{E}}{\delta p\cos\varphi\, d\varphi\, dz}\\
&-\frac{a^2}{g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2}\underset{\text{F}}{\overline{uv}\cos\varphi\sin\varphi\, d\lambda\, d\varphi\, dp}\\
&-a^3\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\underset{\text{G}}{\overline{\rho uW}\cos^2\varphi\, d\lambda\, d\varphi}
\end{aligned}\qquad(1)$$

If the lower boundary is the earth's surface the surface frictional torque

$$+a^3\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\underset{\text{H}}{\overline{\tau_{0\lambda}}\cos^2\varphi\, d\lambda\, d\varphi}$$

will also come in.

In the above,

a=mean radius of the earth
g=acceleration due to gravity
Ω=angular velocity of the earth; u and v, the westerly and southerly components of the wind
p=pressure
δp=pressure difference between the eastern and western boundaries of mountains
W=vertical component of velocity
$dp=-g\rho\, dz$
$\bar{\tau}_{0\lambda}$=mean surface stress along the x-direction

The bar denotes averaging with respect to time and the dashes denote deviation from this time-mean.

The terms A, B, and G of equation (1) denote the flux divergence at the east-west, north-south, and top-bottom boundaries respectively. C is the Coriolis or the Ω-transport term. D arises from the pressure-gradient between the eastern and western walls. E gives the mountain torque. H is the surface frictional torque. The terms A and D reduce to zero when integrated around a latitude circle.

We shall estimate the different terms from mean charts [16], rawin data of stations at the boundaries (fig. 1), and mean contour height and surface pressure charts. The vertical integration is done separately for the westerlies and the easterlies, i.e. from 1000 mb. to 500 mb. and 500 mb. to 100 mb.

3. THE Ω-TRANSPORT TERM

The Ω-transport term is computed from the v components derived from Raman's [16] charts. The winds were picked out at 5-degree grid intervals and the v components were found. The integration along the latitude is done similar to Berson and Troup [3] by writing the term as

$$\frac{2\Omega a^3}{3g}\int_{\lambda_1}^{\lambda_2}\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2}\bar{v}d(\cos^3\varphi)d\lambda\, dp$$

and plotting $\bar{v}$ against $\cos^3\phi$ (fig. 5). This term is quite large as found by Berson and Troup [3] in the Australian region. It is of the same order of magnitude in the lower and upper tropospheres but of opposite sign.

4. FRICTIONAL TORQUE

Rao [19] pointed out that the monsoon westerlies lose angular momentum to earth in contrast to the rest of the Tropics. The frictional stress at a given place along the x-direction is taken as

$$\tau_{0\lambda}=\kappa\rho uV \qquad (2)$$

after Priestley [14], where V is the total speed of the wind. The constant $\kappa=0.0013$ was used. The mean surface winds at 5-degree squares from Ramage's[3] analyses using Netherlands surface [10] data were utilized. As the winds are quite steady, taking the time-variation of direction of the wind into account may not considerably improve the value. The torque was computed over the ocean area and was assumed to be of the same rate over land also. The torque is large and compares well with the value got by Berson and Troup [3] for the Indian region.

5. FLUX DIVERGENCE

The mean fluxes at the eastern and western walls involving $\bar{u}^2$ and at the northern and southern walls involv-

[3] These analyses were made by Ramage at the International Meteorological Centre, Bombay; unpublished.

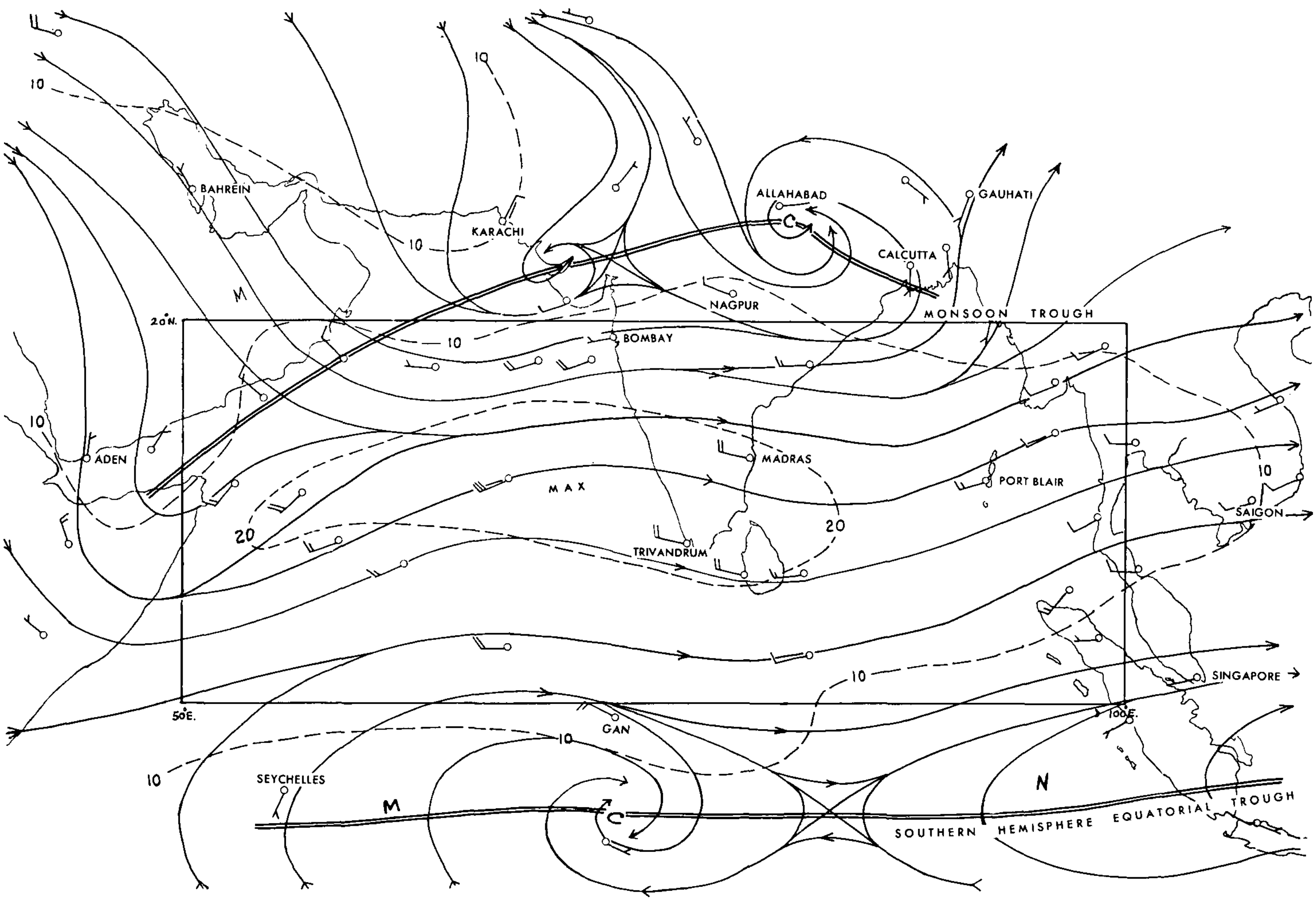

FIGURE 1.—Mean-wind chart for July, 700 mb. Solid line, streamline; dashed line, isotach.

ing $\overline{u}\overline{v}$ were computed from the mean wind data from charts. The flux divergence is small in the lower troposphere but quite large in the upper troposphere.

The eddy fluxes were computed for stations around the boundary shown in figure 1, using I.I.O.E.[4] rawin data for 4 months—July–August 1963–64. These were normal monsoon seasons. The eddy fluxes at the eastern and western walls were estimated from wind data of Aden (12.8°N., 45.0°E.) and Saigon (10.8°N., 106.7°E.). The divergence of this eddy flux is small both in the lower and upper tropospheres.

The meridional eddy flux was computed at all the stations shown in figure 1. In the upper troposphere Rao's [19] values for Singapore and Nairobi were used. The field of this flux was analyzed for the lower and upper tropospheres (figs. 6 and 7) and from these charts the flux divergence was estimated. This procedure was adopted as the meridional flux varies considerably from longitude to longitude. This flux divergence is also small.

The meridional flux charts show some interesting features. There is actually divergence of this flux from the region of maximum winds. So it is possible that the zonal kinetic energy is being converted into eddy kinetic energy. An inspection of the figures 6 and 7 would show that the eddy fluxes at many of the stations have the same sign as that of $\overline{u}\overline{v}$. This would indicate that the eddy fluxes are accomplished, perhaps, more by pulsations of the speed rather than by traveling wave-type disturbances. Actually there is convergence of the meridional flux in the region of weak winds near the seasonal trough (monsoon trough) from Arabia to North India.

Figure 8 shows the vertical profile of $\overline{u'v'}$ at Nagpur (21.1°N., 79°E.) and Gan (0.7°S., 73.1°E.), at the northern and southern ends of the zonal winds, respectively. This transport is maximum near the level of the easterly jet.

6. ZONAL PRESSURE GRADIENT TERM

The zonal pressure gradient term can be rewritten as

$$\delta\left\{-a^2\int_{\varphi_1}^{\varphi_2}\int_{z_1}^{z_2} p\cos\varphi\, d\varphi\, dz\right\}$$

$$=\delta\left\{-a^2\int_{\varphi_1}^{\varphi_2}\int_{p_1}^{p_2} z\cos\varphi\, d\varphi\, dp\right\} \quad (3)$$

[4] International Indian Ocean Expedition.

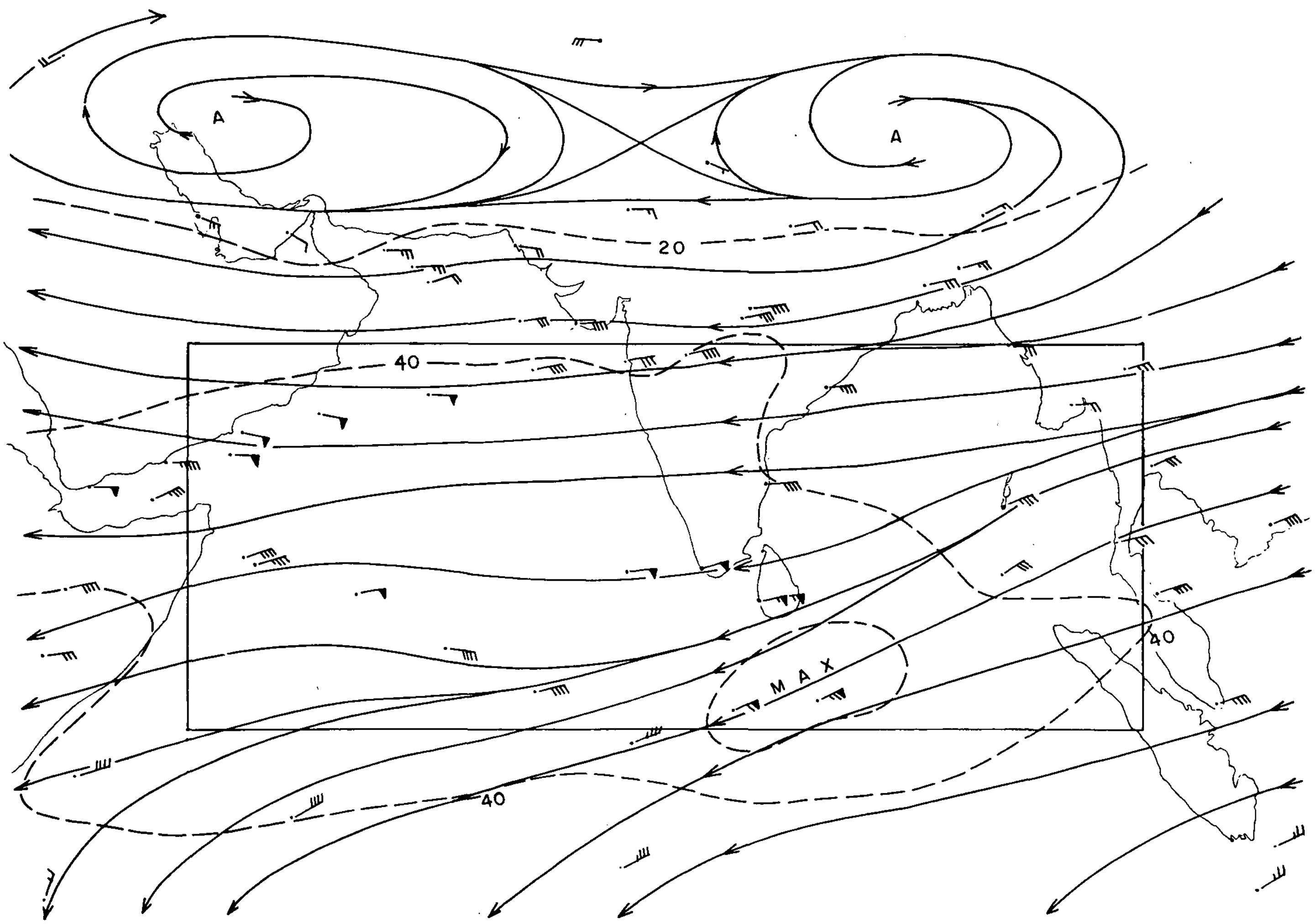

FIGURE 2.—Mean-wind chart for July, 200 mb. Solid line, streamline; dashed line, isotach.

where z is the height of a constant pressure surface and δ indicates the difference between the eastern and western walls. This term is estimated from the height difference between the eastern and western walls. The heights were picked out at 5-degree latitudes from mean contour analysis for July done for an earlier paper [17]. This term is small in the lower troposphere. It is considerable in the upper troposphere. The estimates would indicate that the meridional component is not geostrophic, contrary to the observations of Berson and Troup [3]. If a very narrow region around the Equator is considered, perhaps this term may be more important than the Coriolis term. Frost and Stephenson [5] pointed out that the simplest way of explaining the equatorial westerlies and upper easterlies is that they form a simple zonal circulation cell with ascending motion over heated Indonesia and descending motion over equatorial Indian Ocean near 60°E. This type of situation occurs in the transition months of March–April.

The term E of equation (1) is obviously small. In term F the eddy flux at 100 mb. can perhaps be assumed to be small. As our integration is from 1000–500 mb. and 500–100 mb. the vertical flux at 500 mb. also comes in. This is difficult to compute and can be obtained only as a balance.

7. MOUNTAIN TORQUE

A rough estimate of the mountain torque is made for the Western Ghats (near the west coast of Indian peninsula) and the hills of Burma. Only surface pressure data are available on the eastern and western sides of the hills. Rawinsonde data are too sparse for computation. From the mean surface pressure data of stations on the eastern and western sides, δp was computed; δp was assumed to be zero at about 2 km. which is roughly the height of these mountain ranges and a linear variation of δp was also assumed between surface and 2 km. as done by White [26]. The torque is 1.7×10^{25} gm.cm.^{2}sec.$^{-2}$ for the Western Ghats and 0.4×10^{25} units for the Burma hills. No pressure data were available to the author for the hill ranges in Sumatra. But, from an inspection of available mean surface pressure maps, no large pressure gradient is observed in that region. So, perhaps, the torque in that region is not considerable. The surface pressure data used are for coastal stations

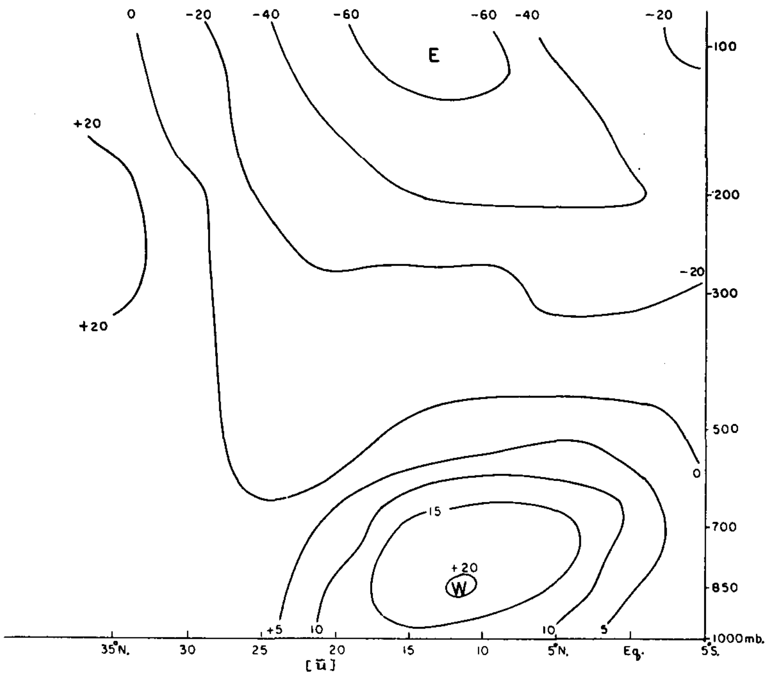

FIGURE 3.—Mean zonal wind (kt.) for July averaged between 50°E. and 100°E. $[\bar{u}]$.

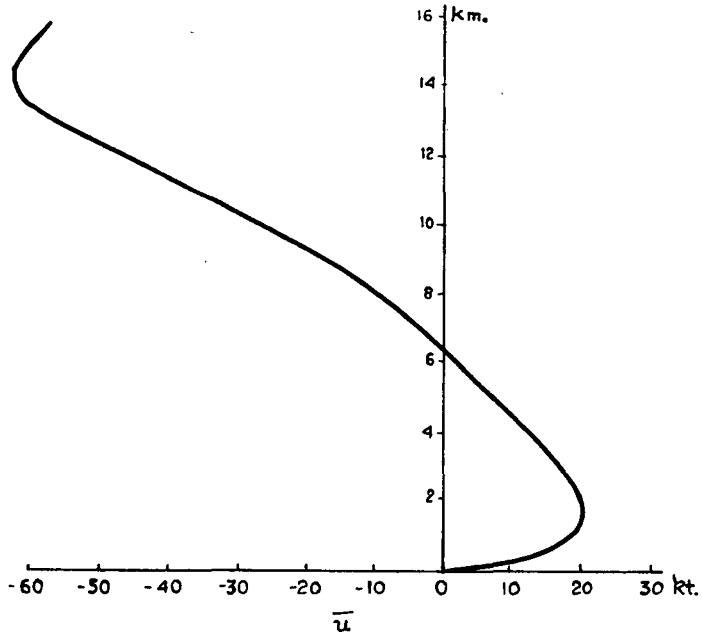

FIGURE 4.—Mean zonal wind at Trivandrum (8.5°N., 76.9°E.) (July–August 1963–64).

(almost sea level) on the western side of the hills and for somewhat higher level stations on the eastern side of hills; some systematic pressure difference may be introduced due to the reduction to sea level.

8. BALANCE OF ANGULAR MOMENTUM

It is seen in table 1 that the main source term for the zonal angular momentum is the Coriolis or the Ω-transport

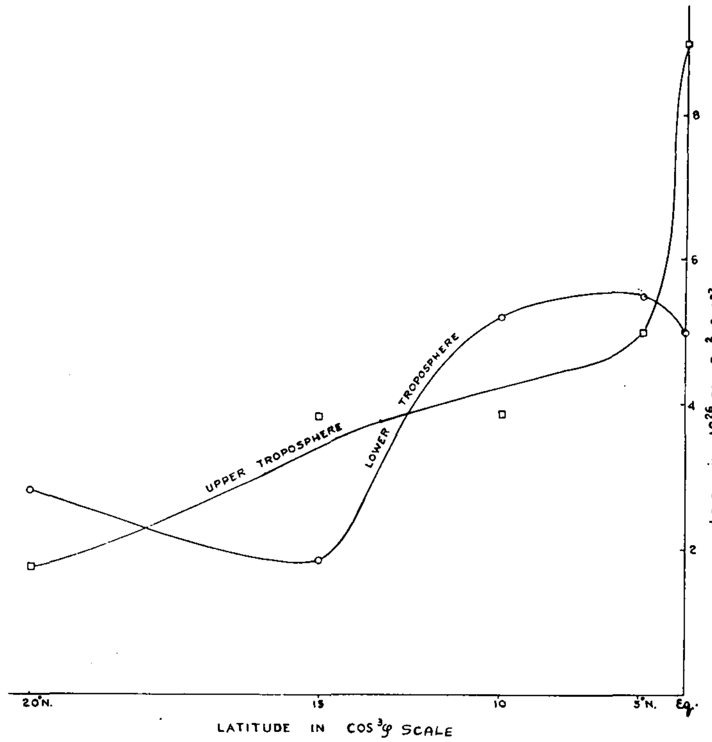

FIGURE 5.—$\Omega\text{-term} = \frac{2\Omega a^3}{3g}\int_{50}^{100E}\int_{P_1}^{P_2} \bar{v}\, d\lambda\, dp.$

term. The frictional torque is large but the Ω-term is large enough to maintain the lower tropospheric westerlies against friction. The zonal pressure gradient term is smaller. The zonal momentum is produced in the region rather than being advected from outside. In the lower troposphere the flux-divergence at the boundaries is small; in the upper troposphere it is large and serves to export the easterly momentum produced in the region. As there is good balance between the various terms, separately in the lower and upper tropospheres (within the limits of accuracy) it is not necessary to postulate any large vertical flux at 500 mb.

The Ω-term means that the meridional component, by Coriolis turning, results in the zonal winds. This result is in accordance with the Murakami's [5] model experiment of the Indian monsoon. The meridional circulation is induced by diabatic sources. Figure 9 shows the meridional components averaged between 50°E. and 100°E. taken from

TABLE 1.—*Budget of angular momentum. Units: 10^{25} gm. cm.^{2} sec.$^{-2}$*

	Lower troposphere (westerly momentum positive)	Upper troposphere (easterly momentum positive)
Ω-transport or Corolis term	6.8	7.0
Frictional torque	−7.0	
Zonal pressure gradient term	−0.4	2.6
Mountain torque	2.1	
Flux divergence;		
East-west Mean	−0.3	−5.0
East-west eddy	−0.4	0.5
North-south Mean	0.3	−4.8
North-south eddy	−0.1	−0.5
Balance	1.0	−0.2

[5] Personal discussions.

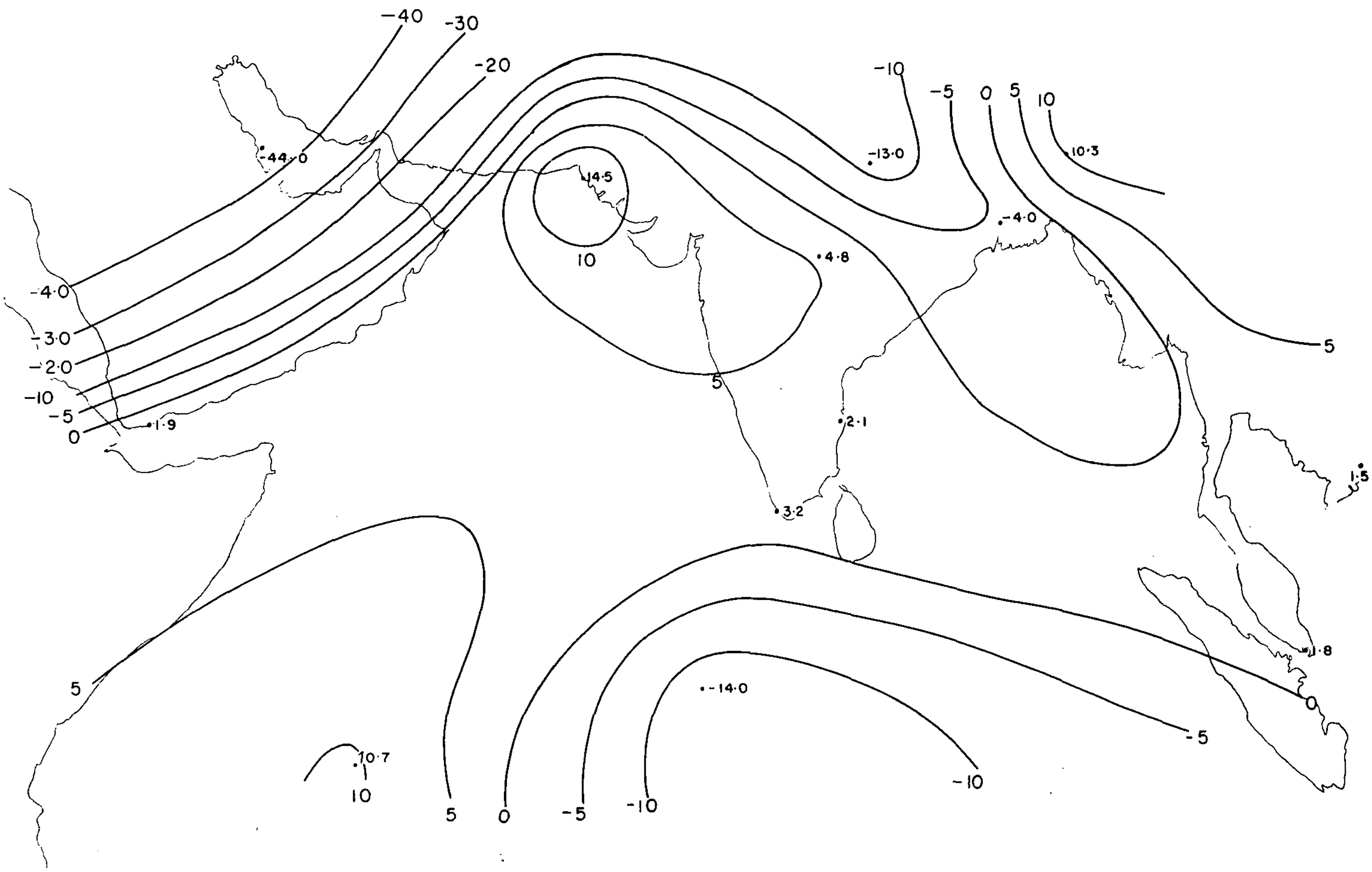

FIGURE 6.—Meridional eddy transport of momentum, lower troposphere: $\frac{1}{g}\int_{500}^{1000} \overline{u'v'} \cos \phi \, dp$ in 10^6 gm. sec.$^{-2}$

mean charts. It shows a meridional cell with southerlies in the lower troposphere and northerlies in the upper troposphere. The continuance of the cell across the Equator suggests that the Southern Hemisphere winter Hadley Cell crosses into the Northern Hemisphere as observed by Palmén [11], Berson and Troup [3]. Asnani and Pisharoty [2], however, found that this cell does not transport much moisture from the Southern Hemisphere since the air subsides and dries up on approaching the Equator.

9. ON ENERGY CONVERSIONS IN THE MONSOON

It is known that in the extratropics the conversion of energy in the atmosphere is as shown in figure 10. The conversion of zonal available potential energy into zonal kinetic energy occurs through the intermediaries, synoptic eddies. But, in the monsoon, the mean meridional circulation being more important than the eddy mechanisms, the zonal available potential energy is being directly converted into zonal kinetic energy by "y-p" overturnings.

Pisharoty [13] found that the Tropics are a source region of kinetic energy, the major part of the production being by the mean meridional circulation (during winter). The Indian monsoon is no exception. After Palmén et al. [12], the kinetic energy released by the mean meridional circulation over a longitudinal belt λ per unit length of the meridian is

$$\frac{\lambda f \cos\varphi}{g}\int_{100}^{1000} \bar{v}\bar{u}_g \, dp, \tag{4}$$

where f=Coriolis parameter.

u_g=geostrophic wind speed along x-direction. Assuming u_g to be approximately equal to $\bar{u}$, $\bar{u}\bar{v}$ should give the kinetic energy release. Figure 11 shows that $\bar{u}\bar{v}$ is positive over most of the meridional cell and is maximum at 1000 mb. and around 200 mb. and is weak in the middle troposphere, as found by Palmén et al. [12]. The mean meridional cell is a direct energy-producing cell. Figure 12 shows the release of kinetic energy at different latitudes. The reaseel in the lower and upper tropospheres are of the same order of magnitude. Integrating this for the whole latitudinal belt we get energy release of 3×10^{10} kw. (fig. 12) (1.2×10^{10} kw. in the lower troposphere and 1.8×10^{10} kw. in the upper troposphere) which is of the same order of magnitude as the release in the winter meridional cell over an equal area which will be about 3.3×10^{10} kw. from the figures of Palmén et al. [12]. If we consider only this term (i.e. not considering other source terms, frictional loss and export at the boundaries), it can

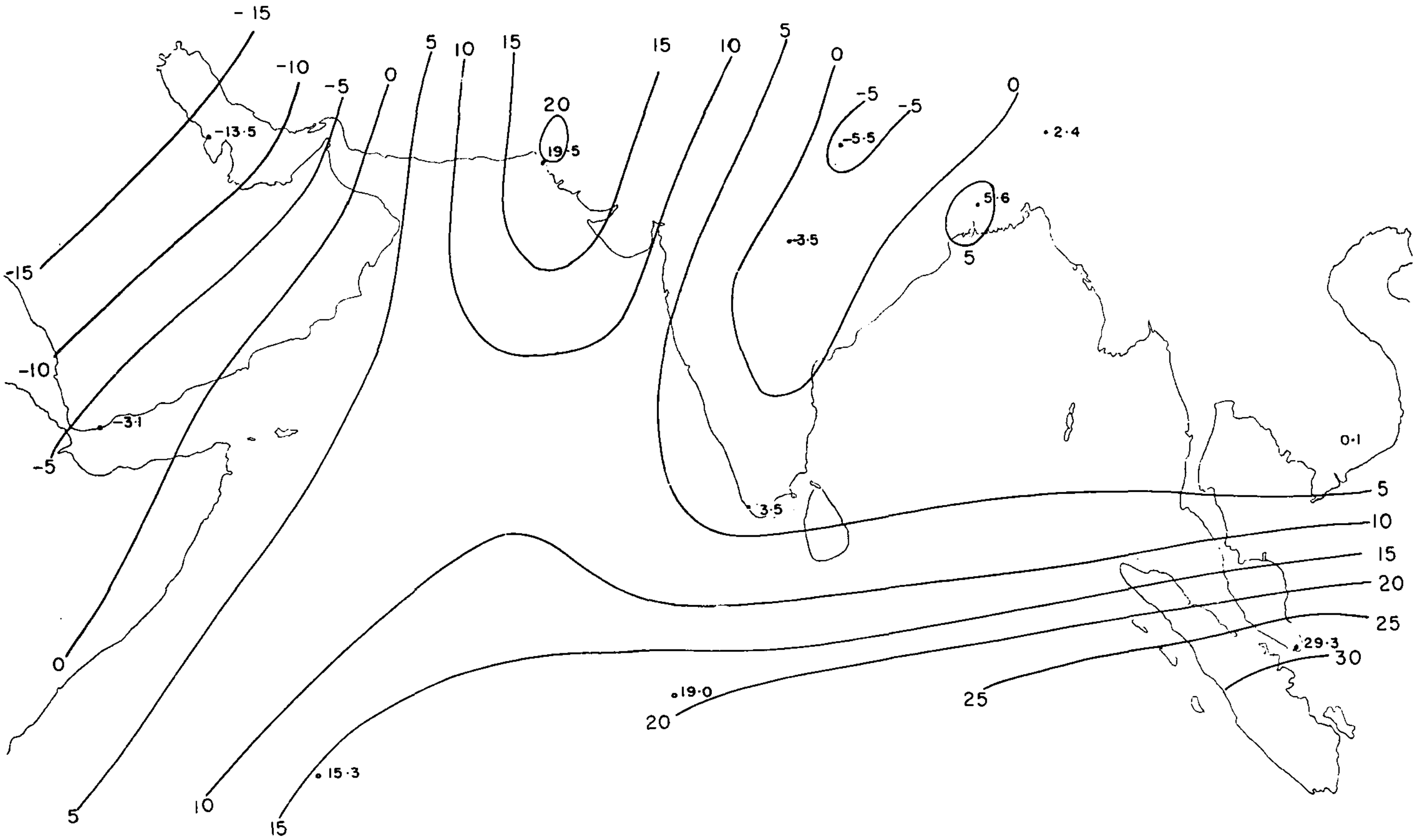

FIGURE 7.—Meridional eddy transport of momentum, upper troposphere: $\frac{1}{g}\int_{100}^{500} \overline{u'v'} \cos \phi \, dp$ in 10^6 gm. sec.$^{-2}$

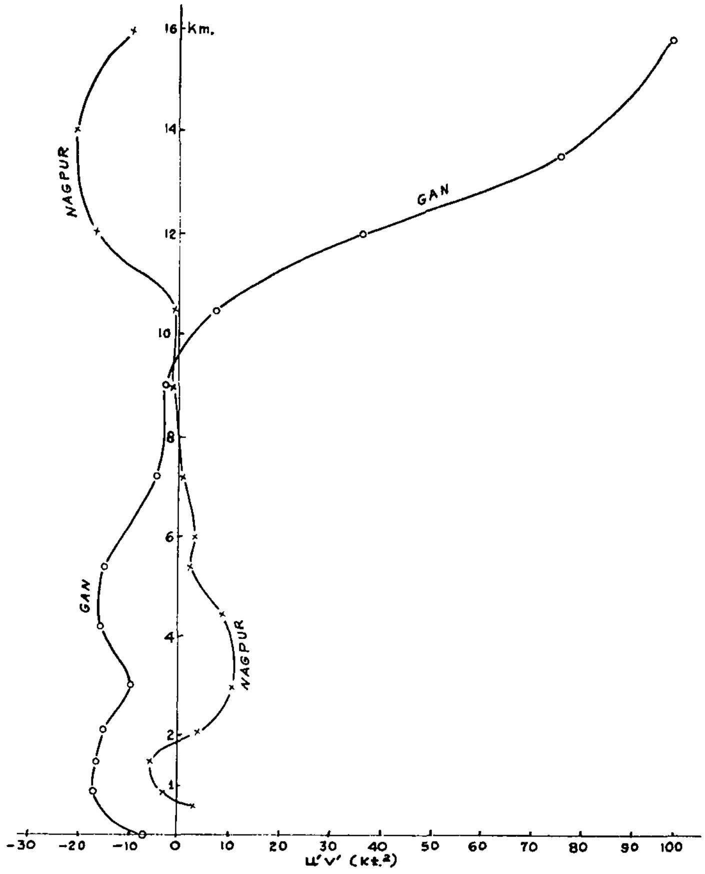

FIGURE 8.—$\overline{u'v'}$ (kt.^{2}) as a function of height (km.).

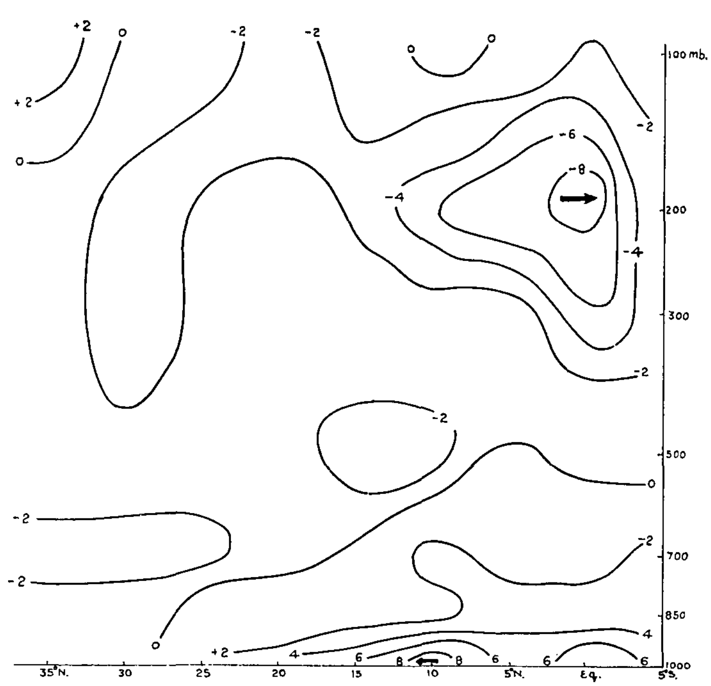

FIGURE 9.—Mean v component (kt.) for July averaged between 50°E. and 100°E. [$\overline{v}$].

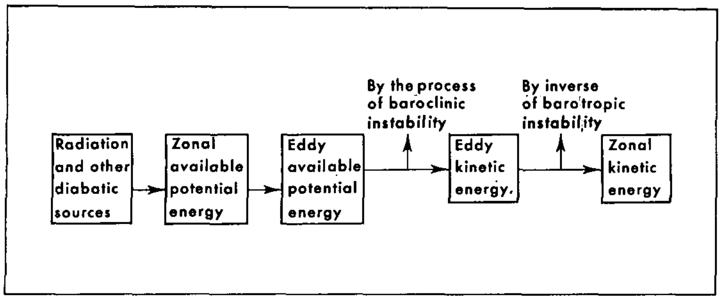

FIGURE 10.—Conversion of energy in the extratropical atmosphere.

replenish the mean zonal kinetic energy in about 3 days. Actually, the meridional cell is of the direct type east of 70°E. or 75°E. and of the indirect type west of this [1, 4, 17, 20]. An average between 50°E. and 100°E. would include both these types and so the mean meridional circulation will be weaker than the direct cell, but still shows energy release; the release in the direct cell may be greater.

Raman et al. [17] and Rama Murthi et al. [15] found that the meridional circulation is stronger over India during a strong monsoon regime. The direct circulation over Southeast Asia and Bay of Bengal extends farther westward to cover parts of Arabian Sea also.

If the mean meridional circulation maintains the mean zonal motion, weak monsoon conditions occurring during the monsoon season or even failure of the monsoon during a season will depend on whether the heat source in the north is weak; this again involves interplay with the midlatitude westerly systems. Such interactions between the monsoon and the midlatitude systems have been studied by Ramaswamy [18].

10. LIMITATIONS OF THE DATA

The Ω-transport term and the zonal pressure gradient term are based on wind and height analyses and to that extent involve subjectivity. However, the wind charts [16] include some aircraft mean winds over the sea areas. For the zonal pressure gradient term, the contour heights are required only at the eastern and western walls where rawinsonde stations are available. The mean flux divergence is also based on the same wind analyses; but, in the upper troposphere where this flux is large, aircraft wind data are available near the boundaries (fig. 2).

The eddy flux terms are based on data of up to 4 months during 1963–64. These were normal monsoon years and so perhaps these fluxes are quite representative.

11. CONCLUSION

i). In the budget of angular momentum over the Indian monsoon region the Coriolis or the Ω-transport term is the main source term. This term contributes enough to maintain the lower tropospheric westerlies against friction.

ii). The zonal momentum is produced in the region rather than being advected from outside. The flux divergence at the boundaries is small in the lower troposphere; it is large in the upper troposphere and serves to export the easterly momentum produced in the region. Also, there is divergence of eddy flux from the region of maximum winds.

iii). The mean meridional circulation largely contributes to the maintenance of the mean zonal motion. The mean meridional circulation releases kinetic energy of the same order of magnitude as the mean winter meridional cell over an equal area.

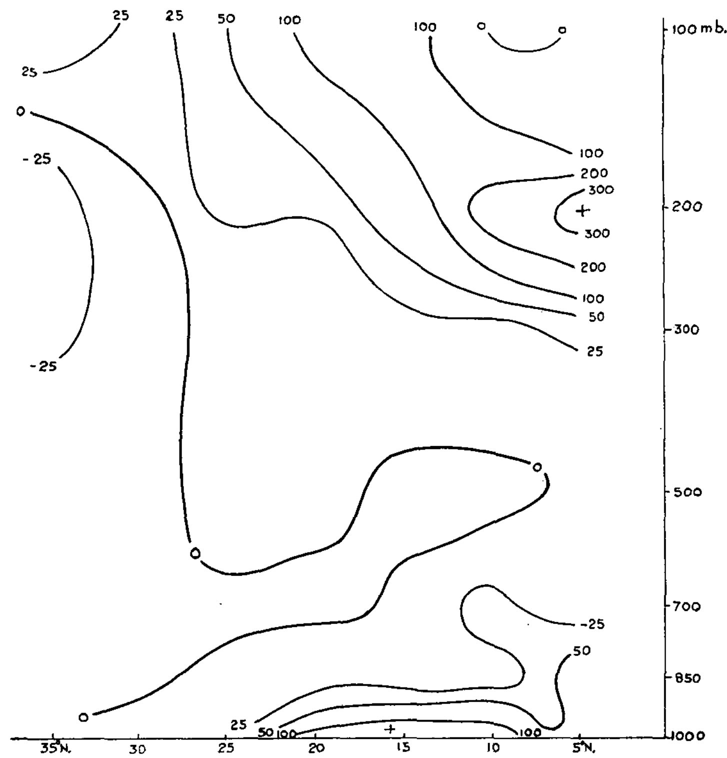

FIGURE 11.—$[u][v]$ (kt.^{2}) as a function of latitude and pressure. Square bracket indicates averaging between 50°E. and 100°E.

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[6] Now back at Meteorological Research Institute, Tokyo, Japan.

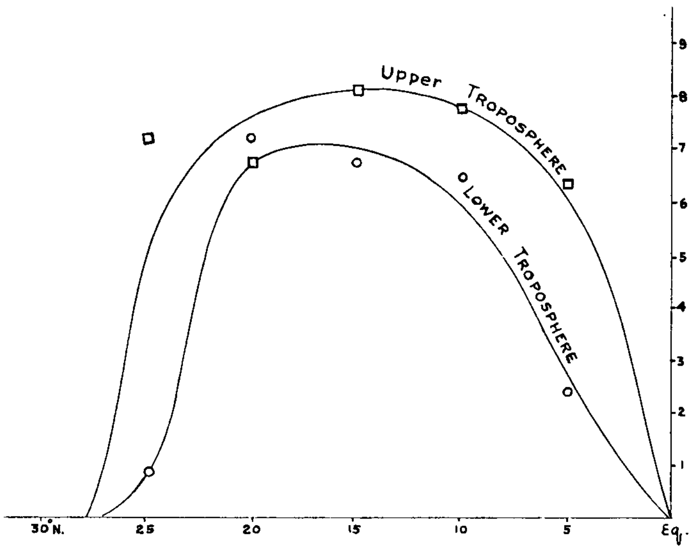

FIGURE 12.—Kinetic energy released by the mean meridional circulation per unit length of latitude.

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